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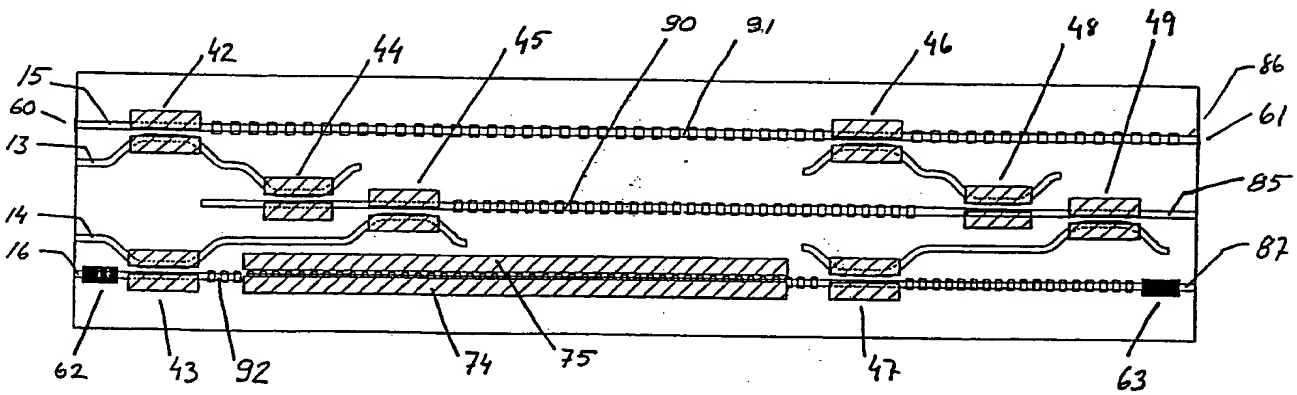

(57) Abstract

The present invention concerns a coherent light source based on frequency conversion of the radiation from two lasers (20, 21) by frequency mixing in optical waveguides (10; 90), which are provided in a substrate (1). The wavelengths for the two lasers (20, 21) should be such, that the phase matching condition for the optically nonlinear frequency conversion is fulfilled in the waveguide structure (10; 90). The frequency conversion is accomplished in the form of frequency mixing, frequency doubling or down conversion in frequency by parametric oscillation so that in total three or four new wavelengths can be generated. By using integrated optics technique the output radiation can be controlled in various ways, for example be switched to different output waveguides, varied in intensity or colour balance.

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Light source

The present invention relates to light sources which are based on frequency conversion of radiation from lasers with moderate output powers, such as semiconductor lasers.

It is of great interest to construct small, compact, power efficient, narrow linewidth, and inexpensive light sources in the visible wavelength range. Small efficient light source are available in the near infrared wavelength region in the form of semiconductor lasers. With some difficulty also semiconductor lasers emitting in the visible part of the spectrum can be made. Primarily the value of the bandgap in the semiconductor material limits the possibility to generate shorter wavelengths. In the same way there exist a large interest for compact and power efficient light sources at longer wavelenghts in the infrared, than is obtainable with regular semiconductor material.

Research is under way on different semiconductor materials to try to develop compact and reliable light sources at new wavelengths, but many problems remain to be solved.

An alternative approach to reach new wavelengths is to use nonlinear effects, as frequency doubling, sum-frequency generation, difference-frequency generation and parametric oscillation for frequency conversion of available laser frequencies. Especially frequency doubling is a common method to generate new wavelengths from certain high power laser systems, which are used particularly in research laboratories. For lasers with moderate output powers this method is more difficult to apply, primarily because the conversion efficiency for frequency conversion is too low in this case.

To obtain a satisfactory conversion efficiency for nonlinear processes, such as frequency doubling and sum-frequency generation, high intensities are required

over comparatively long interaction lengths. By using an optical waveguide, especially a so-called channel waveguide, a focused laser beam can be confined within a small cross section area (and thereby high intensity) over long interaction lengths without being diffracted. This means that in a waveguide provided in a good optically nonlinear material, it can be possible to obtain a high conversion efficiency even for lasers with low output power. The primary limiting factor for practical applications is that the so-called phase-matching condition must be fulfilled.

Lithium niobate ($LiNbO_3$) is a material that has a comparatively high nonlinearity and in which it is also possible to fabricate waveguides of high quality and long lengths (several cm).

The so-called phase-matching condition, which must be fulfilled to achieve an efficient wavelength conversion, can for frequency mixing (sum- or difference-frequency generation) be written:

$$k_3 = k_1 \pm k_2 \qquad (1a)$$

or equivalently:

$$\frac{2\pi N_{eff,3}}{\lambda_3} = \frac{2\pi N_{eff,1}}{\lambda_1} \pm \frac{2\pi N_{eff,2}}{\lambda_2} \qquad (1b)$$

with:

$$\frac{1}{\lambda_3} = \frac{1}{\lambda_1} \pm \frac{1}{\lambda_2} \qquad (2)$$

where λ_1 and λ_2 are the two pump wavelengths ($\lambda_1 \leq \lambda_2$), while λ_3 is the generated wavelength, and whereby the plus sign corresponds to sum-frequency generation and the minus sign to difference frequency generation. $N_{eff,1}$, $N_{eff,2}$ and $N_{eff,3}$ are the so-called effective refractive indices in the waveguide at these three wavelengths, respectively. In the special case of frequency doubling, the plus sign applies together with $\lambda_1 = \lambda_2$ and $N_{eff,1} = N_{eff,2}$. Phasematching means that the generated radiation is propagating with the same phase velocity as the driving nonlinear polarization. The phase

velocities are determined by the effective indices, and to fulfil the phase matching condition the refractive indices at the three wavelengths must comply with the condition given by equation (1b). In the case of frequency doubling this corresponds to equal effective indices at the fundamental and the frequency doubled wavelength. The same equations are valid for parametric oscillation, provided that the plus signs are used and that λ_3 corresponds to the pump wavelength, whereas λ_1 and λ_2 correspond to the generated wavelengths. In the case of degenerated parametric oscillation only one wavelength is generated, i.e. $\lambda_1=\lambda_2$.

To achieve phasematching in waveguides most often the birefringence of the material is utilized, whereby the interacting waves are differently polarized. For sum-frequency generation in lithium niobate ($LiNbO_3$) the light at the two pump wavelengths experience the polarization corresponding to the ordinary refractive index while the generated wave is experiencing the extraordinary polarization. From the dispersion curves for the ordinary and the extraordinary refractive indices of $LiNbO_3$, schematically shown in Fig.1, it can be seen that only wavelengths around 540 nm can be generated by frequency doubling and sum-frequency generation. However, a certain amount of tunability can be obtained by a different choice of the two pump wavelengths used in sum-frequency generation or by varying the temperature of operation. In the first case the nonlinearity of the dispersion curve is used, while the second case relies on different temperature dependency for the ordinary and the extraordinary refractive indices. One can also obtain some wavelength shift by doping of the substrate for instance with MgO or proton exchange and by changing the design of the waveguide (which affects the waveguide dispersion). It is well-known that waveguides in $LiNbO_3$ are suitable for

frequency doubling as well as for sum-frequency generation, difference-frequency generation, parametric oscillation and parametric amplification. In such experiments, however, almost exclusively gas lasers and solid-state lasers have been used. For example, it has been demonstrated that, with radiation from a Nd:YAG laser (1.064 µm wavelength), high conversion efficiency for frequency doubling can be obtained at relatively low pump powers in lithium niobate waveguides, fabricated in either doped or undoped substrate material. Frequency doubling in lithium niobate waveguides according to this scheme has, however, not yet been applied for semiconductor lasers due to the phase-matching difficulties.

Today reliable semiconductor lasers are available primarily in three wavelength regions: around 0.8 µm (based on GaAs), around 1.3 µm (based on InP) and around 1.55 µm (based on InP). None of these wavelengths can be phase-matched for frequency doubling in conventional lithium niobate waveguides.

However, it is known that radiation from diode lasers at wavelengths around $\lambda = 0.8$ µm can be frequency doubled in so-called proton exchanged waveguides, with the frequency doubled light generated in the form of Cerenkov radiation. The light is then generated as a radiation mode propagating into the substrate. It has been possible to construct a small compact light source this way, with the wavelength in the visible range. A disadvantage with this technique, is that the nonlinear process is less efficient as compared to the case when coupling takes place between two guided waves. Another disadvantage is that waveguide cross-section has to be extremely small in practice. This leads to very high light intensities in the waveguide and a tendency to light induced changes in the waveguide that detrimentally affect the stability of the frequency

doubling, especially at continuous wave operation. The light is also emitted in a cone under the waveguide, which makes it difficult to collimate and focus the light.

Another known technique for frequency conversion in waveguides is to utilize so-called quasi-phase-matching in periodically domain inverted waveguides in $LiNbO_3$ or $LiTaO_3$ (lithium tantalate). Quasi-phase-matching is a more generally useful phase-matching method because the possibility to achieve phase-matching is not limited by the amount of the birefringence in the material. It is, however, technically more difficult to fabricate the required waveguide structure. Quasi-phase-matching waveguides can be used to frequency double, for instance 0.85 µm and 1.3 µm wavelengths, thereby generating blue and red light, respectively. Quasi-phasematched frequency doubling can not be used to generate green light, however, due to shortage of semiconductor lasers at the required fundamental wavelength.

It is also known that appropriate/adequate/relevant nonlinear optical materials, such as $LiNbO_3$, $LiTaO_3$, KTP ($KTiOPO_4$), $KNbO_3$ (potassium niobate) etc., also have high electro-optical material coefficients, and that consequently the electro-optic effect advantageously can be used for steering/control/switching and modulation of the light. There are known methods to control light by using various integrated optical components, for example in order to couple part of the light from one channel waveguide to another either in a fixed, predeterminded way or in a varyable way, or in order to modulate the intensity, phase or phase velocity of the light in a channel waveguide.

There are known methods based on the use of various integrated optical components for controling light (propagating in a channel waveguide) for example for coupling part of the light from one channel waveguide to

another either in a fixed predetermined way or in a variable way and for modulationg the intensity, phase or phase velocity of the light in a channel waveguide.

Metal electrodes arranged on the crystal surface, either on top of the waveguide or beside it, to which electric drive voltage are applied, are used for adjustment and modulation. Modulation using the electro-optic effect can be done with low drive voltage and high modulation frequency, and no mechanically mobile parts are required. It is also known that many integrated optical components, active as well as passive, are wavelength selective.

To be able to realize a small, semiconductor laser pumped frequency doubler based on conventional waveguides in $LiNbO_3$ requires a comparatively powerful diode laser at a wavelenght of around 1.08 µm. It is only this wavelength (approximately), that can be phasematched for frequency doubling in $LiNbO_3$ waveguides at room temperature and today such lasers are not available. Corresponding restrictions to a narrow (wavelength) interval for the fundamental wavelenth(s), for which frequency doubling can be achieved in practice, applies also to other nonlinear materials as $KNbO_3$, KTP, $LiTaO_3$, BBO (β-BaB_2O_4), LBO (LiB_3O_5), etc. This illustrates the main problem with frequency conversion, which is to solve the phase-matching problem in a way as general as possible in order to be able to utilize available laser frequencies and nonlinear materials.

One prerequisite/condition is that today, diode lasers that are easily available, single mode, have long life (time?), and relative high output powers mainly exist at three limited wavelength regions: 780-850 nm (based on GaAs) and around 1300 nm and 1550 nm (in both the latter case based on InP substrates).

To be able to integrate light sources of different wavelengths on the same substrate, would be of great value for many applications like displays, optical scanning, optical registration, image generation etc.

For a number of applications is it further of great interest to have a possibility to easily modulate the intensity of the light source and/or to select its wavelength from a number of alternative wavelengths, or to change the color balance of the light source, by varying the relative intensities of a number of different wavelength components included in the light source.

The purpose of the present invention is to accomplish compact light sources, particularly in wavelength regions where no semiconductor lasers are available, by efficient frequency conversion of radiation from semiconductor lasers (or other compact, power efficient lasers) in waveguides, and thereby in a flexible way solve the phase-matching problem so that as many wavelengths as possible can be generated from available laser wavelengths and available nonlinear optical materials. The purpose is also to enable generation of several wavelengths from the same device (the same substrate) and easily with electrical control signals be able to modify the properties of the light source: select one wavelength from a number of available wavelengths, vary the color balance between a number of wavelengths that the light source consists of, modulate the intensity of the light source rapidly etc.

The invention provides solutions to the present problems in the way described in the characterizing parts of the five patent claims enclosed. Here it is assumed that a waveguiding structure is arranged in an optically nonlinear material as $LiNbO_3$, doped $LiNbO_3$, $LiTaO_3$, KTP, $KTiOAsO_4$, $KNbO_3$, BBO, LBO, NYAB or corresponding substances, and that efficient frequency conversion can be

accomplished in this waveguide structure, due to the fact that the radiation for all the wavelengths present can be confined within a small cross-section area over a comparatively long interaction length (several cm).

The invention is characterized in that <u>two</u> semiconductor lasers (or other low power lasers) are used to pump the nonlinear frequency mixing process (sum- or difference-frequency generation), whereby the lasers used have such wavelengths that the phase-matching condition is fulfilled either by utilization of the birefringence of the material in combination with the waveguide dispersion or by utilization of so-called quasi-phase-matching technique.

The invention is further characterized by the fact that the same device can yield radiation at several wavelengths, due to the fact that apart from the new frequency generated by frequency mixing, also both of the pump frequencies are available, as well as due to the fact that each of these two pump frequencies can separately, and preferably in separate channel waveguides, be frequency doubled or down converted in frequency through parametric oscillation (or through the special case of <u>degenerate</u> parametric oscillation).

The invention is in also characterized by the possibility to combine the channel waveguides where the frequency conversion takes place, with integrated optical components, based on known technique, which components can be wavelength selective and preferably electro-optically controllable, to adjust the fulfilment of the phase-matching condition and couple the radiation into, out of, or between channel waveguides, in such a way that with electrical control signals it is possible to vary the properties of the light source (alternatively it is possibly to design a device with certain predetermined properties) in one or several of particularly the

following regards: select one wavelength from a number of available wavelengths (which include both the two pump wavelengths as well as the new wavelengths generated in the device), separate and direct the radiation of different available wavelengths to different output channel waveguides and modulate the intensity at each wavelength, combine and direct light of different wavelengths into one common output channel waveguide or into adjacent output waveguides, control the relative intensities or the color balance between a number of wavelength components comprised in the light source. A special case is when the integrated optical components are designed for fixed, predetermined functions.

For phasematching based on the use of birefringence the material dispersion and waveguide dispersion together with the temperature dependence of the refractive indices at the wavelengths involved, determines which wavelengths that can be phase-matched by equation (1) and (2).

For quasi-phasematching the relation between the wavelengths is still given by equation (2). Equation (1) does not have to be fulfilled, and instead the phase-mismatch which is present, is compensated for, in the known way, by an appropriately chosen periodicity of the quasi-phasematching waveguide.

The invention includes a combination of different elements, each of which when taken separately corresponds in many cases to known technique. However, the invention is also based on a thorough analysis, both theoretical and experimental, to define combinations that are of practical interest, and to determine under which conditions these are realistic.

We have for instance from calculations found that sum-frequency generation can be obtained between GaAs lasers and InGaAsP lasers at temperatures around, and just above, room temperature in waveguides fabricated by

titanium indiffusion in $LiNbO_3$ (in undoped and MgO doped crystals). Using two such lasers (operating at or close to two commonly occuring wavelengths: 0.85 µm and 1.3 µm or 1.55 µm, respectively) and a $LiNbO_3$ waveguide, it is possible to build a small, compact coherent source generating visible (green) radiation, which is of great practical interest. We have also demonstrated this principle in a laboratory experiment by mixing radiation from two diode lasers at 0.85 µm and 1.31 µm wavelengths in a channel waveguide fabricated by titanium indiffusion in lithium niobate and thereby generated light at 0.508 µm. In this experiment the birefringence of the material together with the waveguide dispersion was used to fulfil the phase-matching condition. By in this way using sum-frequency generation the invention makes it possible to fulfil the phase-matching condition at a temperature close to room temperature, using available materials and semiconductor laser wavelengths, in cases where the phase-matching condition for frequency doubling of the individual laser wavelengths were not possible, as well as makes it possible to generate green light from semiconductor lasers which has not been possible by frequency doubling because of the lack of laser diodes at an appropriate wavelength.

Another application example is that according to the invention the sum-frequency generation can also be combined with frequency doubling of radiation from the two individual pump sources separately, so that for instance if two infrared laser diodes are used as pump sources the possibility exist to generate three different wavelengths in the visible within the same substrate. If two semiconductor lasers at wavelengths around 0.85 µm and 1.3 µm, respectively, are used, then three different wavelengths can be generated in the visible: namely blue and red by frequency doubling and green through

sum-frequency generation. Obviously many applications exist for such a light source giving both blue, green and red light.

The invention is described in closer detail below with reference to the attached figures 2 - 15.

Figure 2 shows the invention in one of its simplest embodiments (embodiment 1). A channel waveguide 10 is fabricated in the surface layer of a substrate 1 of an optical nonlinear material. Radiation from two laser diodes 20 and 21, are combined via the lenses 30 and 31 and a wavelength selective beam splitter 32 and are then coupled by a lens 33 into the channel waveguide 10 in the substrate 1. The light at the new wavelenght generated in the waveguide is passing out through the output end-face of the channel waveguide, possibly together with nonconverted radiation at the two pump wavelengths. The two latter wavelengths can, if desired, be excluded, with an optical component 34, in the form of a filter or a polarizer, at the output end-face of the channel waveguide.

The radiation from the two pump sources can be combined and launced into the channel waveguide where the frequency conversion takes place, in a number of ways. The most obvious method is to use a dichroic beamsplitter 32 which transmits one of the wavelengths and reflects the other, as already described and as illustrated in Fig 2. Examples of other methods to combine the radiation are given in Figs. 3 - 5. All the Figures 2 - 5 exemplify different versions of embodiment 1 of the invention.

Figs. 3 and 4 show versions, relying on couplers integrated in the waveguide substrate. In Fig. 3 the light from the two channels 13 and 14 are geometrically brought together through a coupler 40 (a Y-coupler) into the common main channel waveguide 10.

In Fig. 4, a wavelength selective coupler of known type is used, with the design parameters chosen so that the radiation propagating in both of the two incoming channel waveguides 13 and 14 are efficiently coupled into the common straight main waveguide 10, where the nonlinear frequency conversion is accomplished. The wavelength selective coupler is in the figure illustrated in the form of a directional coupler (with the interaction length chosen to get the desired coupling), but also other types of integrated optical couplers according to known technique can be utilized (e.g. Mach-Zehnder interferometers, symmetric or asymmetric X-switches, TIR-switches, BOA-couplers, three-waveguide-couplers, combinations of directional couplers and Mach-Zehnder interferometers, Y-switches, so-called digital switches etc.). To modify the degree of coupling in the coupler, the electro-optic effect can be used.

In both these cases the diode lasers could be mounted just in front of the crystal and microlenses can then be used to launch the light into the channel waveguides through their end-faces. An alternative is so-called butt-coupling whereby the laser diodes are mounted in close proximity to the end-faces of the channel waveguides and the radiation is coupled directly into the guides without the use intermediate optics. The light could as well be launched through short pieces of optical fibrers (so-called fiber pigtails).

Alternatives to a filter or polarizer (34 in Fig. 2) in order to eliminate the pump wavelengths, are an integrated optical polarizer, a polarization absorber or another integrated optical wavelength selective component.

A third version illustrated in Fig. 5 relies on a fiber-coupler 51 that combines the radiation from the two lasers 20 and 21 whereby the radiation from each laser is launched into one of the two input fibers 52 and 53, and

the common output fiber 54 is mounted ("pigtailed") against the $LiNbO_3$ substrate or the radiation from this fiber 54 is coupled into the channel waveguide by other means. The state of polarization must be well controlled which may require the use of polarization maintaining fiber. Furthermore, the fiber should be single mode at both pump wavelengths. The end of the fibers, into which the radiation from the lasers are launched can be tapered to increase the coupling efficiency.

As mentioned above, an integrated coupler, as number 41 described in connection to Fig. 4, can be tuned electro-optically to obtain the exact desired degree of coupling. This technique can also be utilized for modulation of the radiation. One embodiment of the invention (embodiment 2) which utilizes electro-optically controlled couplers are illustrated in Figs. 6 - 9. The individual couplers are provided with metal electrodes, and electric voltages are applied to these in order to control the degree of coupling at the two wavelengths. One arrangement for such electrodes are schematically illustrated for the coupler 42 in Fig. 6 and the couplers 42 and 43 in Fig. 7. The arrangement in Fig. 7 gives, as compared to the arrangement in Fig. 6, better possibilities to independently vary the degree of coupling from each light source through the input waveguides 13 and 14, respectively, into the main waveguide 10. The couplers are illustrated in the form of directional couplers with two metal electrodes 70 and 71 (72 and 73). To facilitate the control of the coupler, the electrodes might be designed differently, for instance divided into several sections along the channel waveguides. Furthermore there exist, as mentioned previously, a large number of alternative types of couplers or switches. The electro-optic control is also of importance to reduce the fabrication tolerances for a coupler. One can in this way

obtain the desired degree of coupling in spite of a small fabrication error, by applying a correction voltage. A coupler can also be used to modulate the generated light. The generated light can for instance be pulsed in time even though the two diode lasers are radiating continuously.

In a special version, illustrated in Figs. 8 and 9, of the second embodiment, the radiation is brought together from the incoming waveguides (13 and 15 in Fig 8 and 13 and 14 in Fig 9) into the main waveguide 10, as well as coupled out from the main channel waveguide 10 to the adjacent output waveguides 80 and 81, by the use of electro-optically controlled integrated optical couplers/modulators 42, 43, 44, 45 (which are wavelength selective). The invention is characterized in that the radiation which is then emitted from the main channel waveguide through output 85, can be chosen with electrical control signals to consist of one or several of three wavelengths (the wavelength generated by the frequency mixing, and the two pump wavelenghts), and furthermore characterized in that the amplitude of the radiation can be modulated electrically. This embodiment also provides a possibility to separate the three available wavelengths and to obtain each of these separately in three different output channel waveguides 80, 85 and 81, respectively.

In cases when the frequency generation can not be phase-matched using birefringence, there is instead a possibility (according to a third embodiment of the invention, illustrated in Figs. 10 and 11) to utilize for the frequency mixing a so-called quasi-phase-matching waveguide 90, for which the periodicity has been chosen as required for the desired frequency mixing process, according to known technique. See Figs. 10 and 11, which besides the use of a quasi-phase-matching waveguide, are identical to Figs. 8 and 9.

A fourth embodiment implies that the so-far described frequency mixing of two laser sources is combined with frequency doubling or down conversion in frequency through (degenerated) parametric oscillation of the radiation from each of the two pump lasers separately, preferably in separate channel waveguides on the same substrate, whereby primarily but not necessarily quasi-phase-matching technique is utilized. See Figs. 12 and 13. Radiation from the two semiconductor lasers (launched into the input waveguides 13 and 14) can then both be coupled into a channel waveguide 90 where sum- or difference frequency takes place, and radiation from each semiconductor laser, or part of their power, can also coupled into the separate channel waveguides, 91 and 92 respectively, for frequency doubling or parametric oscillation. If two semiconductor lasers with wavelengths around 0.85 and 1.3 μm are used, radiation at three different wavelengths in the visible range can be generated in this way: blue and red light by frequency doubling of the wavelengths 0.85 and 1.3 μm, respectively, and green light by sum-frequency generation. It is further illustrated schematically in Figs. 13 and 14 how the output channel waveguides 86, 85 and 87 can be brought close together, so that at the output they together form a small light source, in which the intensity at the three wavelengths and the balance between them can be controlled electro-optically and at high speed. In Fig. 13 the output channels have been place comparatively close, but so that coupling not necessarily occurs between them; instead each one emits radiation at a specific wavelength and the farfield pattern for each wavelength can thus be controlled by the design of the corresponding waveguide. As illustrated in Fig. 14 the radiation at the three wavelengths can alternatively be brought together into one common output channel waveguide 85 using integrated optical couplers 46, 47, 48, 49, so that a true

point light source is obtained (common for all the wavelengths), in contrast to the version illustrated in Fig 13.

Integrated optical components in combination with other channel waveguides can further be used to separate out undesired parts of the power spectrum at the pump wavelengths, in analogy with Fig 8.

For all the embodiments of the invention the exact phase-matching can be accomplished by temperature tuning of the nonlinear crystal according to known techniques (for instance using Peltier elements), possibly together with electro-optic tuning using metal electrodes along the waveguides. For the lower channel waveguide 92 in Fig. 15 an arrangement for such electrodes 74 and 75 is illustrated. These electrodes can preferably be divided into several sections along the waveguides. This type of electrodes can also be used to indirectly modulate the light.

When fabricating laser diodes a certain variation in the output wavelength is obtained. To get the specific wavelength required for phasematching, the well-known technique of cooling or heating the diode laser can be used.

Nonlinear optical materials useful in this context include: $LiNbO_3$, $LiNbO_3$ doped with e.g. MgO ($MgO:LiNbO_3$) or with Nd and MgO ($Nd:MgO:LiNbO_3$), $LiTaO_3$,, $LiIO_3$, KDP, KTP ($KTiOPO_4$), with KTP isomorph crystals such as $KTiOAsO_4$; furthermore: $KNbO_3$, BBO (β-BaB_2O_4), LBO (LiB_3O_5), NYAB (Neodymium Yttrium Alumiumborate) och CMT (Cadmium Mercery Telluride). Also organic crystals, such as m-NA, MNA, MAP, POM, MNMA, COANP, NPP, DAN, DANS, PNP, and also polymer materials and semiconductor materials, for instance GaAs and InP are of interest.

Waveguide resonators can be used to improve the conversion efficiency for the frequency conversion. Such a resonator could either be a standing wave (Fabry-Perot) device or a ring resonator, and would be necessary for the function in the case of (degenerated) parametric oscillation. A Fabry-Perot resonator can be realized by providing mirrors on the end-faces of the waveguide or with grating reflectors along the waveguide. In Fig. 15 the upper channel waveguide 91 is arranged as a Fabry-Perot resonator with mirrors on the endfaces. The lower channel waveguide 92 is arranged as a resonator using grating reflectors 62 and 63 etched into the surface of the waveguide.

For certain applications it could be useful to adapt a short optical fiber to the output face of the main channel waveguide to be able to transfer the light to a desired position.

In the examples above of the embodiments of the invention the emphasis in the description has been on conversion to shorter wavelengths: primarily conversion to visible light from semiconductor laser wavelengths in the near infrared wavelength region. As mentioned previously, conversion to longer wavelengths for other applications, can be obtained with the same type of components, and with analogous methods; for instance from the usual semiconductor wavelengths to longer wavelengths in the infrared wavelength region. An example is difference-frequency generation of the wavelength 2.1 μm by using pump sources at 0.8 μm and 1.3 μm.

In the detailed description above the pump light sources where in most cases referred to as semiconductor lasers. The invention can obviously also be used in combination with other coherent pump light sources. One such example is so-called semiconductor laser pumped solid

state lasers, which also are comparatively small and compact. Another alternative is semiconductor laser pumped fiber lasers.

In some parts of the description above the term light should be interpreted as covering also invisible radiation: infrared and ultraviolet radiation.

Patent claims

1. A device in the form of a coherent light source based on frequency conversion of radiation from lasers, especially easily available diode lasers, whereby said frequency conversion is accomplished in optical waveguides (10),(90), arranged in a substrate (1) of a nonlinear material like $LiNbO_3$, doped $LiNbO_3$, $LiTaO_3$,, $LiIO_3$, KDP, KTP, $KTiOAsO_4$, $KNbO_3$, BBO, LBO, NYAB, CMT, or similar materials, said device *characterized in that* two lasers (20),(21) are utilized to generate a new laser frequency through frequency mixing (sum- or difference-frequency generation) and in that the two lasers emit radiation at wavelengths such that the so-called phase-matching condition for the optically nonlinear frequency mixing is fulfilled in the said waveguide (10),(90).

2. A device according to claim 1, *characterized in that* the waveguides are designed in such a way, and the two lasers are chosen in such a way, that the wavelengths of their radiation enable fulfilment of the said phase-matching condition by utilization of the birefringence of the crystal material in combination with the waveguide dispersion.

3. A device according to claim 1, *characterized in that* the channel waveguide where the frequency mixing takes place is provided in the form of a so-called quasi-phase-matching waveguide (90), whereby the periodicity of the waveguide is chosen in such a way, according to known principles, that the phase-matching condition for the frequency mixing is fulfilled through quasi-phase-matching.

4. A device according to claim 1 and 2, or according to claim 1 and 3, *characterized in that* the frequency mixing

in a waveguide (10),(90), according to claim 1, is combined with frequency conversion of radiation from the pump sources each individually (or a part of their power), preferably in separate channel waveguides (91),(92), whereby the last-mentioned frequency conversion is accomplished in the form of frequency doubling or by down conversion in frequency by parametric oscillation, so that in this way totally three or four new wavelengths can be generated.

5. A device according to claim 1 and 2, or according to claim 1 and 3, or according to claim 1 and 4, *characterized in that* the channel waveguides (10),(90),(91),(92), in which the optically nonlinear frequency conversion takes place, are combined, coupled together or coupled apart by use of integrated optical components (40),(41),(42),...(49), which are based on known technique and can be wavelength selective and electrically controllable (using the so-called electro-optic effect), in order to couple the radiation into, out of and between the channel waveguides, in which the frequency conversion takes place, and to realize exact adjustment to fulfil the phase-matching condition, so that in this way it is possible with electrical control signals to vary the properties of the light source (alternatively is possible to design a device with certain predetermined properties) in one or several of particularly the following regards: select one wavelength from a number of available wavelengths (which are comprised of the pump wavelengths and new wavelengths generated in the device), vary the intensity of the light source, separate and direct the radiation at the different available wavelengths to different output channel waveguide ports (80), (85), (81), (86), (87) and vary the intensity at the different wavelengths, direct radiation at different

wavelengths into one common output waveguide ((85) in Figs. 14 and 15) or into adjacent output waveguides ((85), (86), (87) in Fig. 13), and control the relative intensities or the colour balance between a number of wavelength components comprised in the light source.

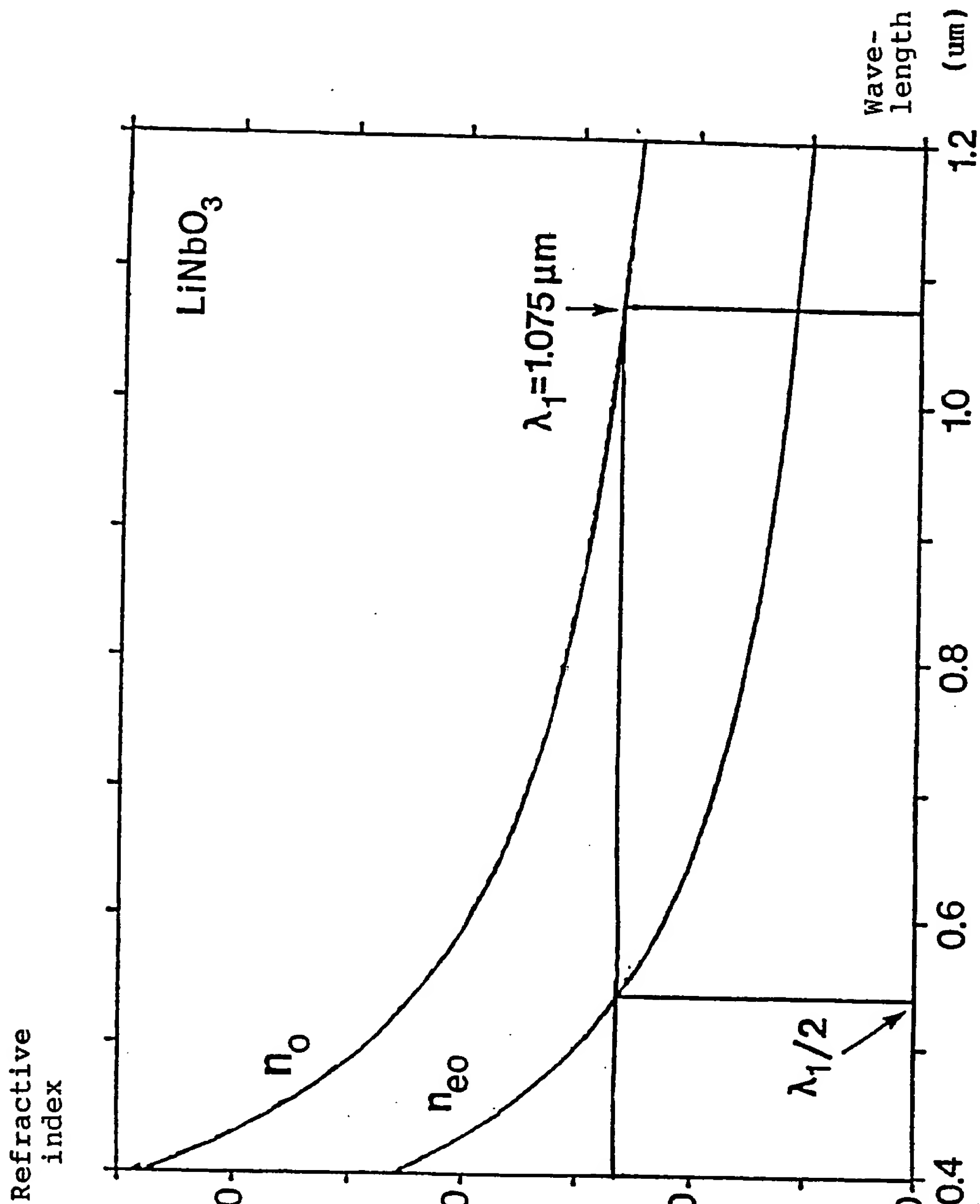
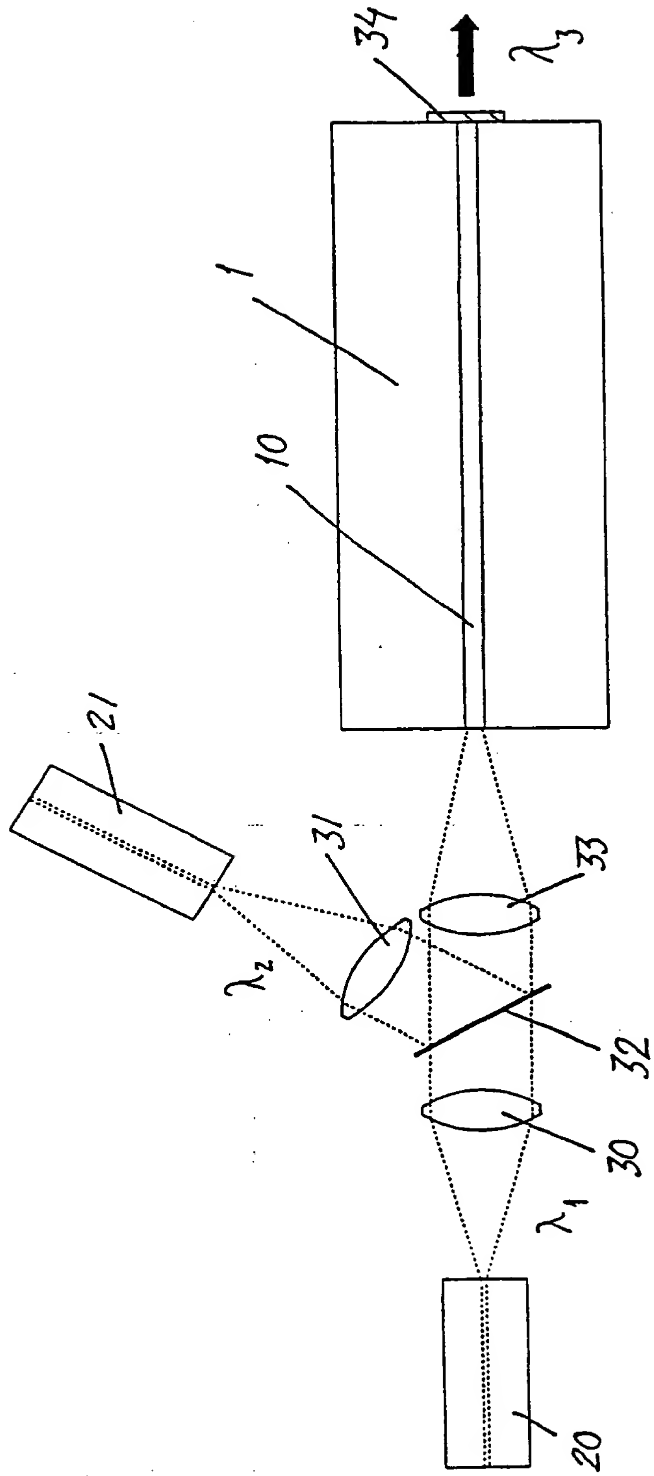

Refractive index
Wave-length (um)
LiNbO3
λ1=1.075 µm
n_o
n_eo
λ1/2
2.40
2.30
2.20
2.10
0.4
0.6
0.8
1.0
1.2

Fig. 1



SUBSTITUTE SHEET

Fig. 2

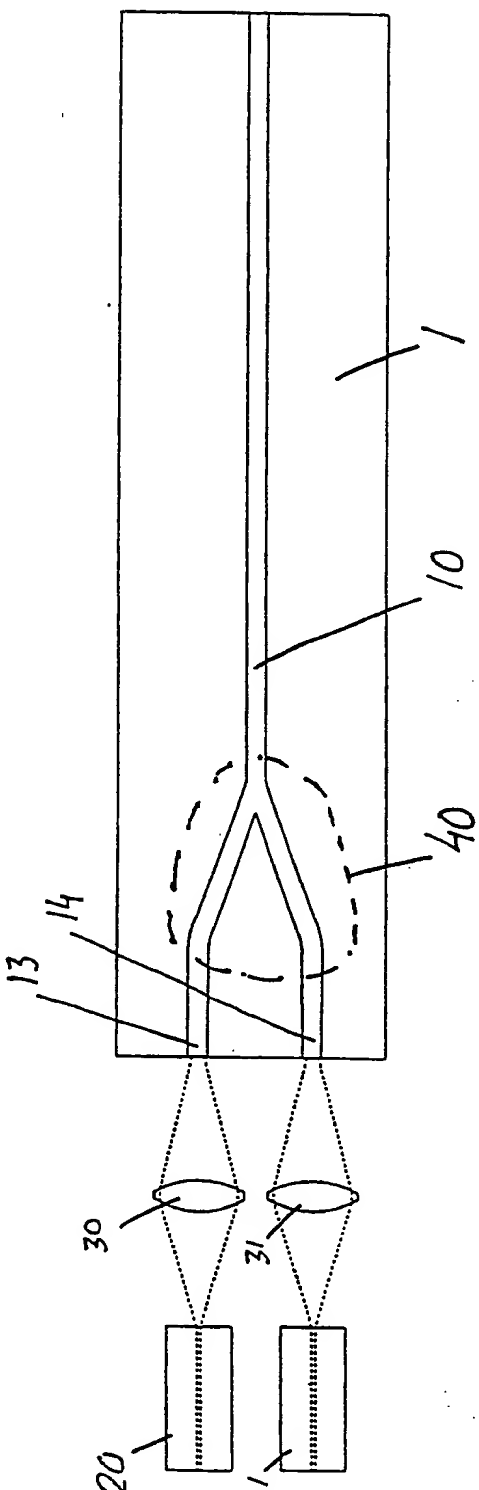


Fig 3

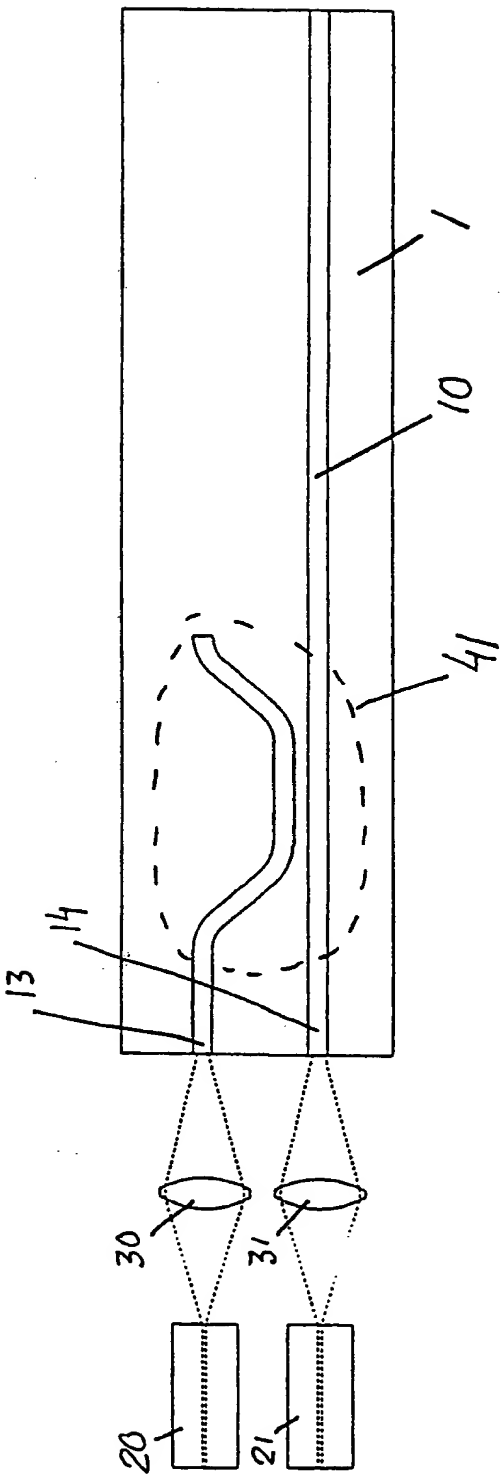


Fig 4

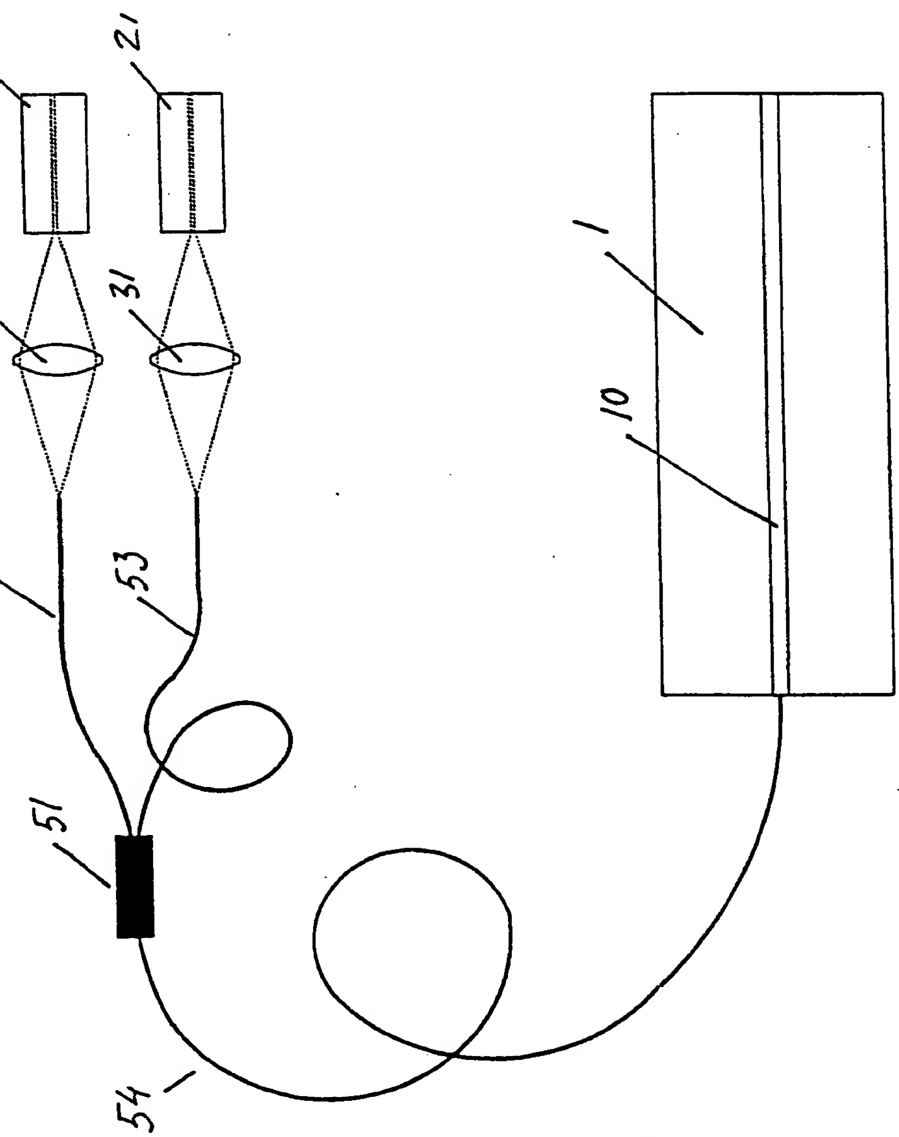


Fig. 5

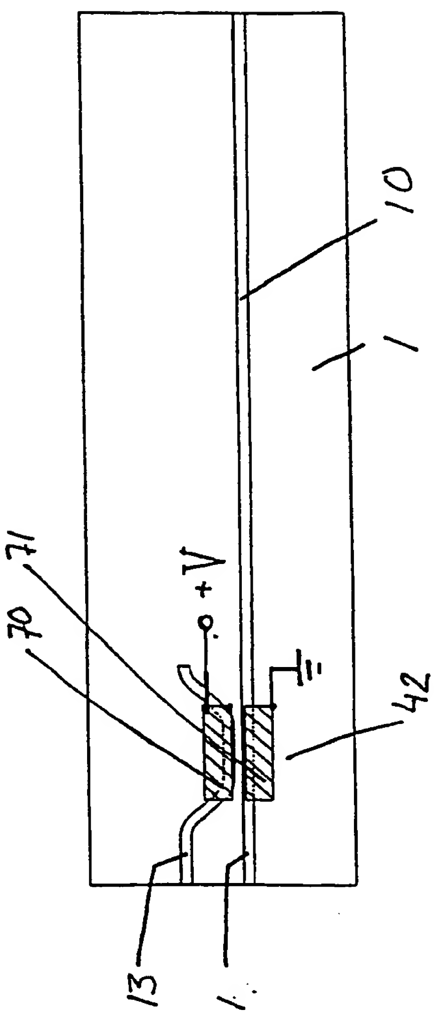


Fig. 6

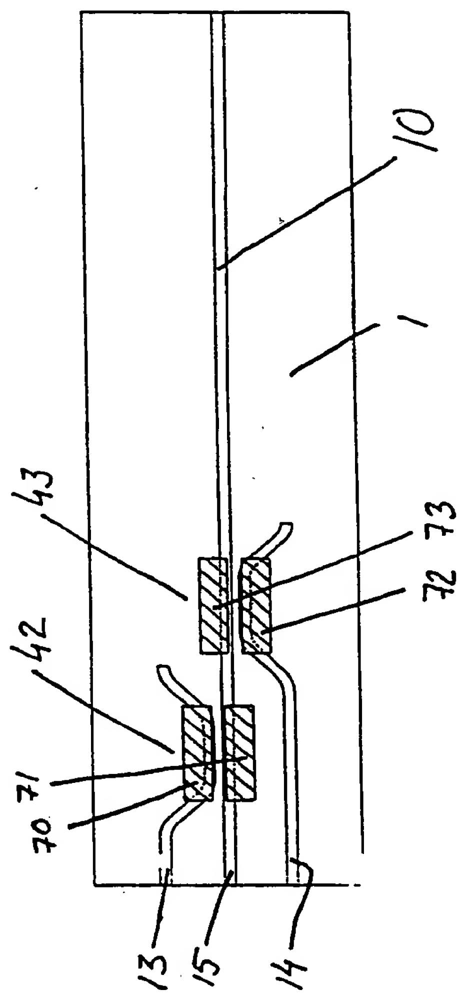


Fig. 7

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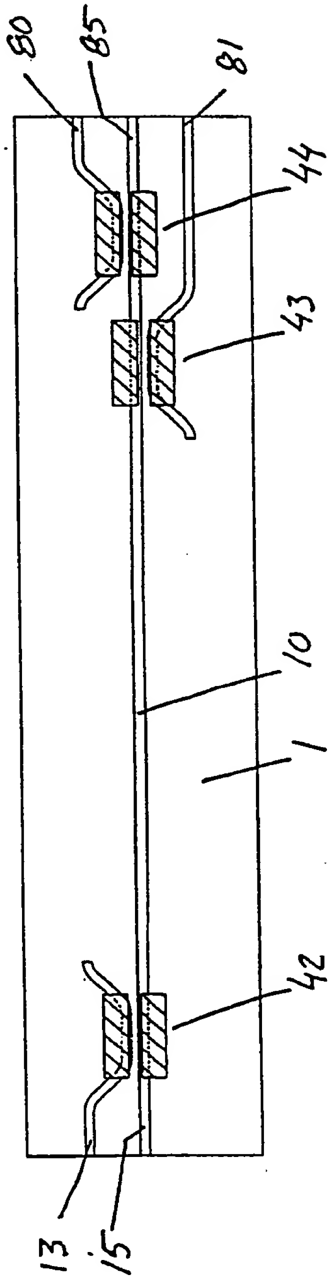

Fig. 8

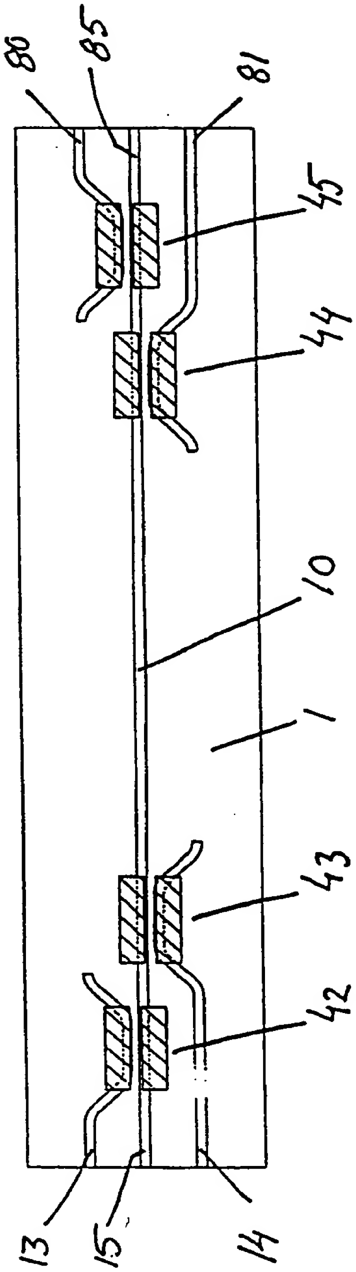

Fig. 9

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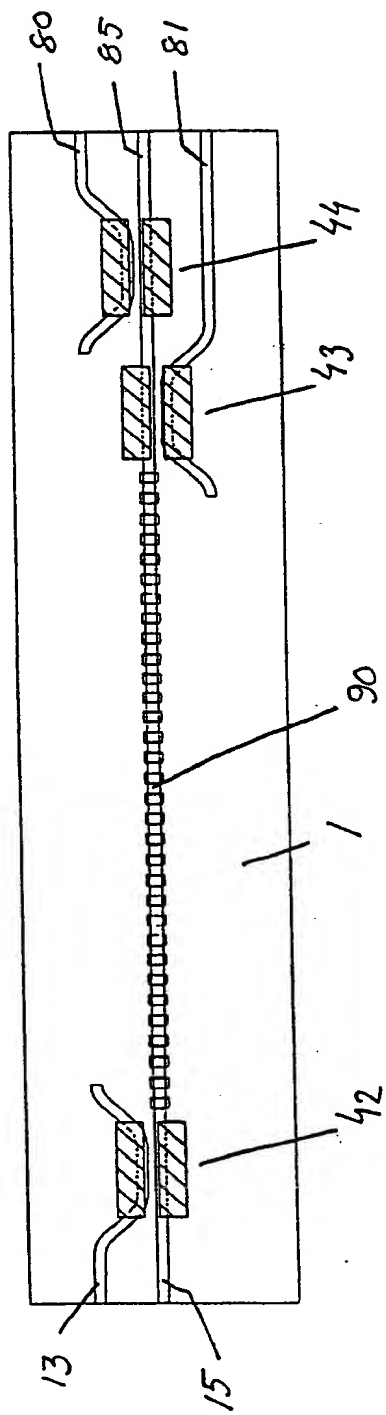

Fig. 10

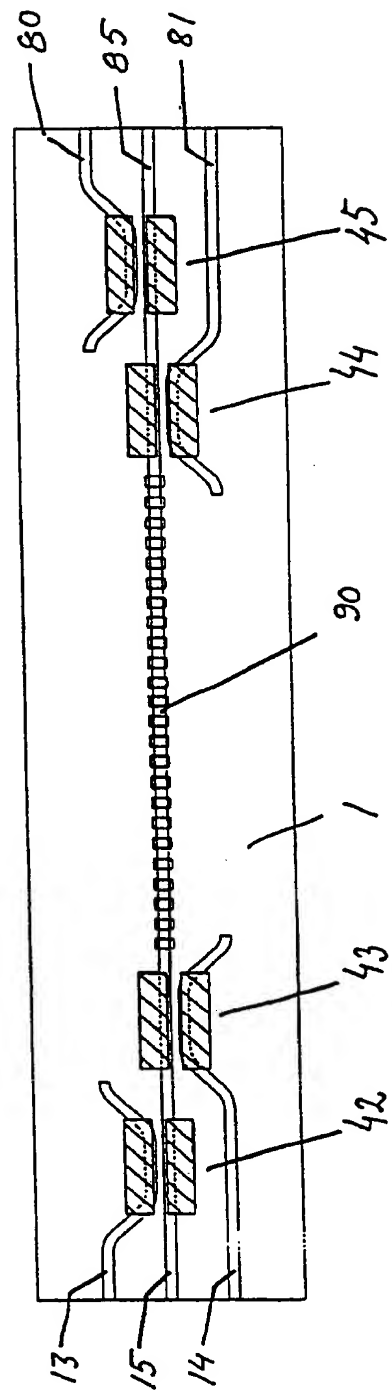

Fig. 11

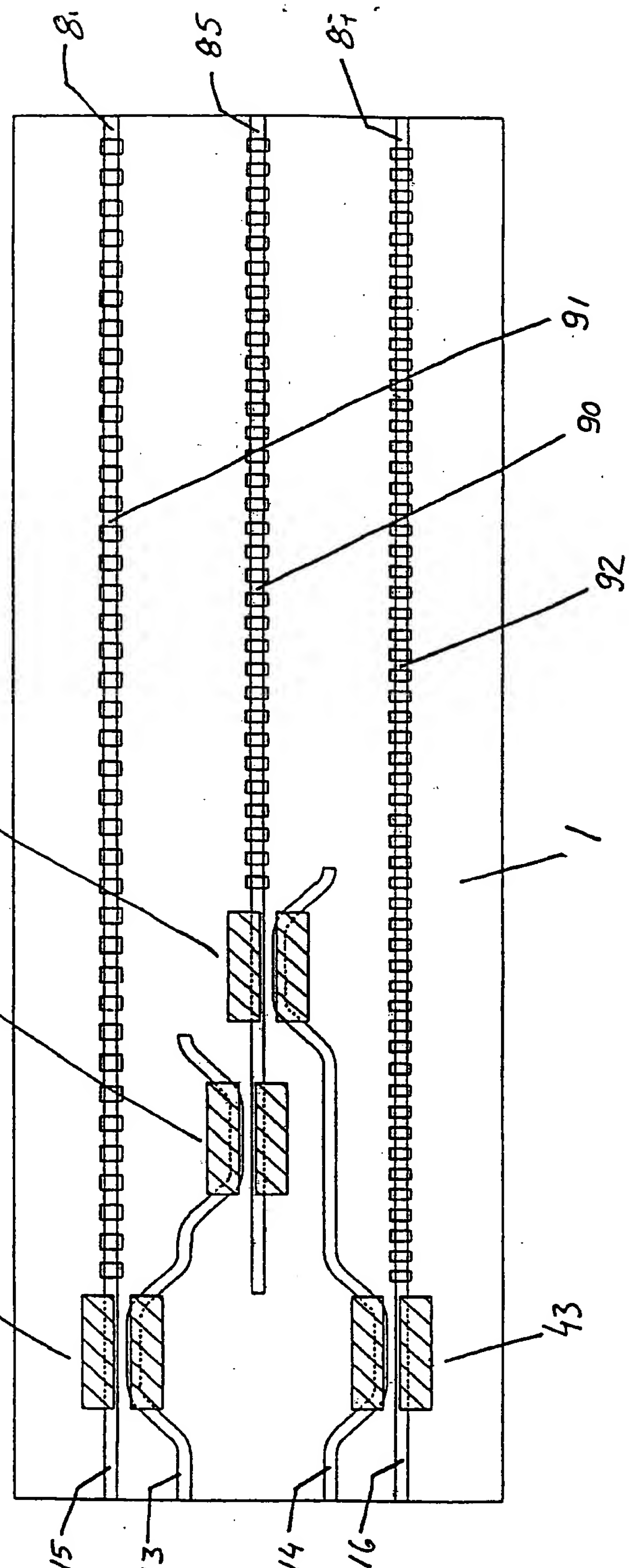

Fig. 12

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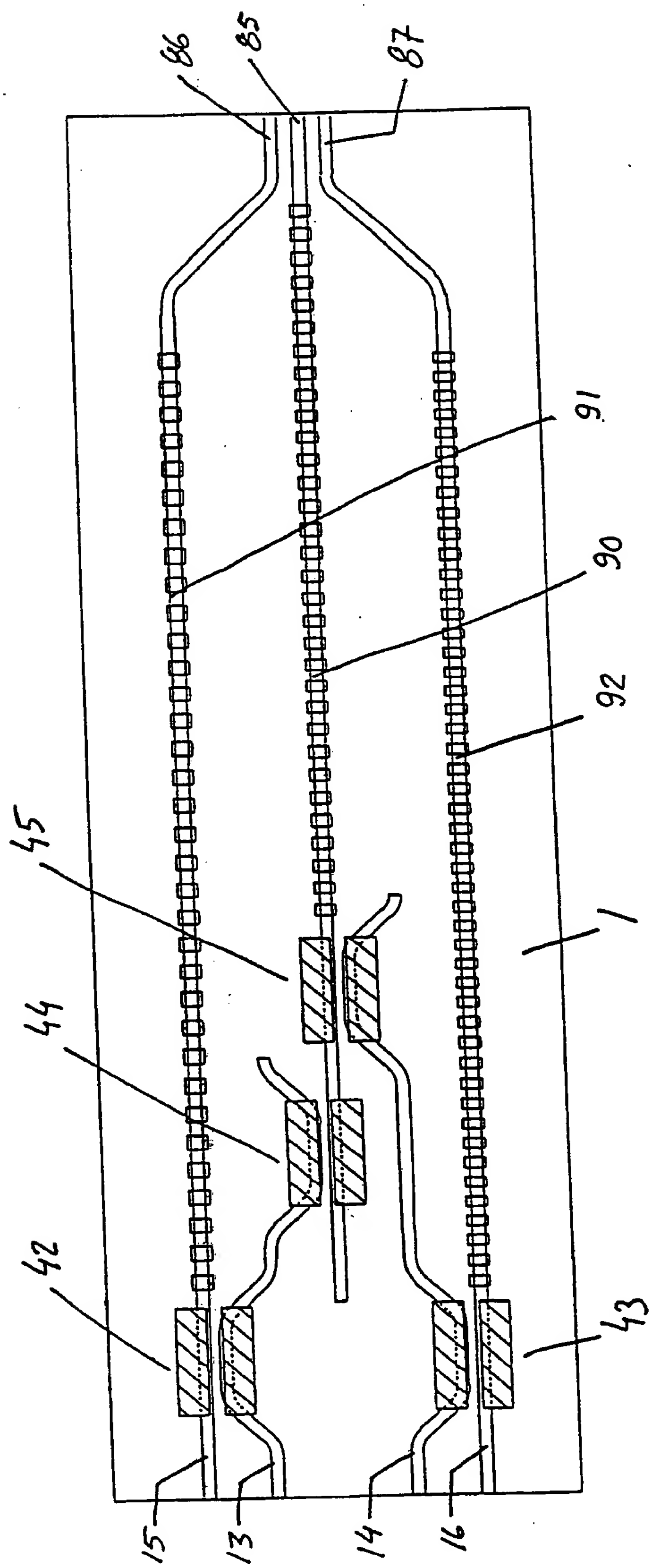

Fig. 13

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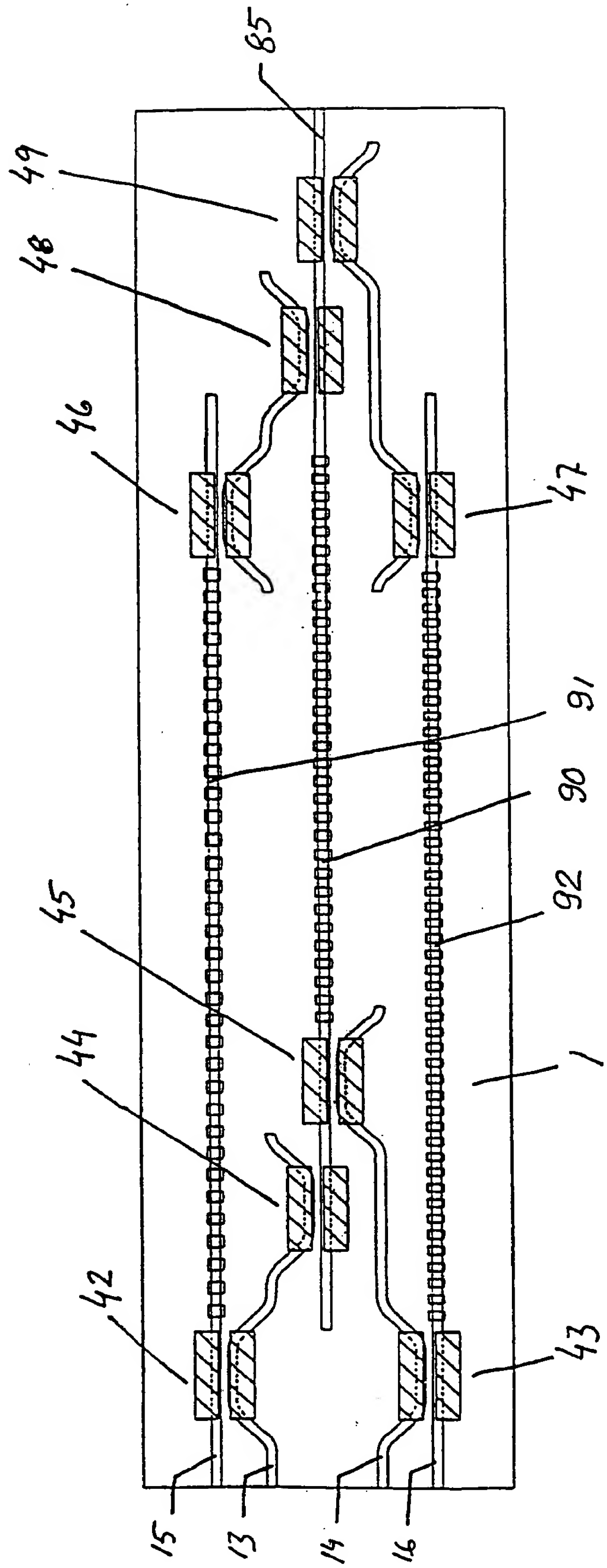

Fig. 14

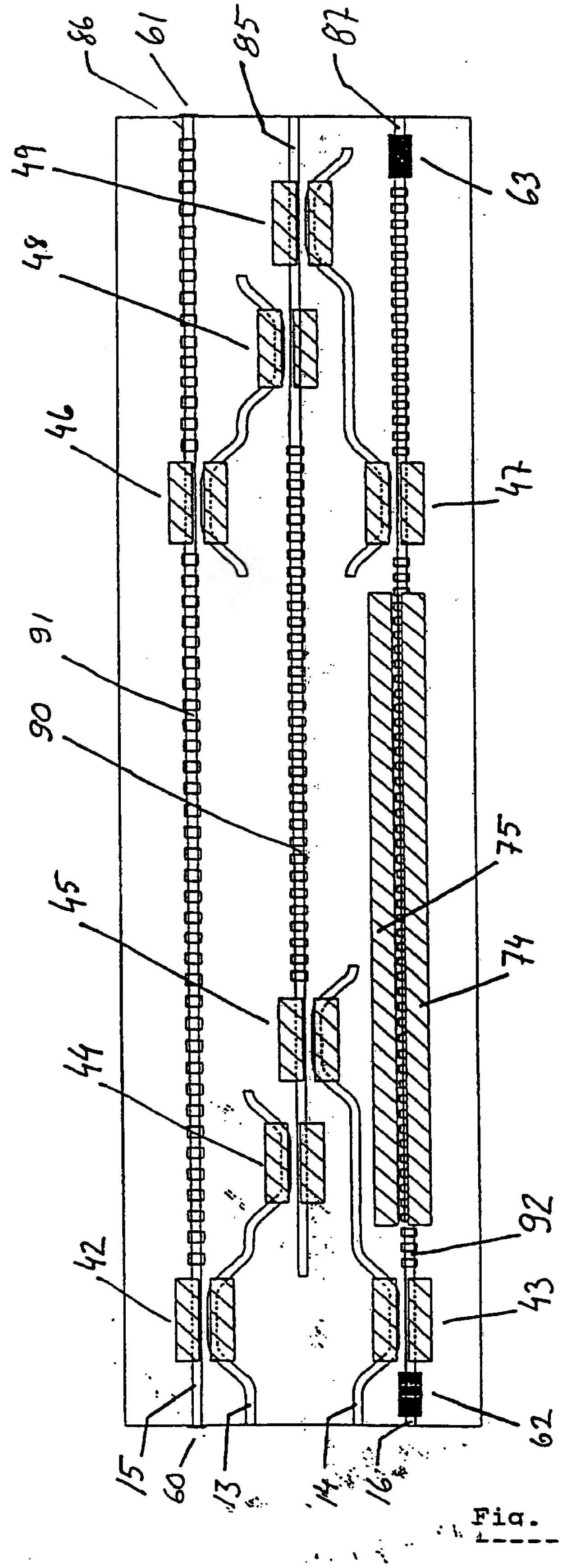

Fig. 15

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INTERNATIONAL SEARCH REPORT

International Application No PCT/SE 91/00095

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC5: G 02 F 1/35, H 01 S 3/13

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
IPC5	G 02 F, H 01 S

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in Fields Searched[8]

SE,DK,FI,NO classes as above

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category *	Citation of Document,[11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
A	EP, A1, 0256964 (TECHNION RESEARCH & DEVELOPMENT FOUNDATION) 24 February 1988, see the whole document --	1-5
A	APPLIED OPTICS, Vol. 17, No. 5, March 1978 S. BLIT ET AL: "CONTINUOUS WAVE UV RADIATION TUNABLE FROM 285 NM TO 400 NM BY HARMONIC AND SUM FREQUENCY GENERATION", see page 721 - page 723 --	1-5

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* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
22nd April 1991	1991 -05- 02
International Searching Authority	**Signature of Authorized Officer**
SWEDISH PATENT OFFICE	RUNE BENGTSSON

Form PCT/ISA/210 (second sheet) (January 1985)

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.PCT/SE 91/00095

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the Swedish Patent Office EDP file on 91-03-23
The Swedish Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A1- 0256964	88-02-24	US-A- 4869579	89-09-26